Biomass Burning Influenced Particles Characteristics in Northern Territory Australia Based on Airborne Measurements

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Abstract

Airborne measurements of particle number concentrations from biomass burning were conducted in the Northern Territory, Australia, during June and September campaigns in 2003, which is the early and the late dry season in that region. The airborne measurements were performed along horizontal flight tracks, at several heights in order to gain insight into the particle concentration levels and their variation with height within the lower boundary layer (LBL), upper boundary layer (UBL), and also in the free troposphere (FT). The measurements found that the concentration of particles during the early dry season was lower than that for the late dry season. For the June campaign, the concentration of particles in LBL, UBL, and FT were (685 ± 245) particles/cm^3, (365 ± 183) particles/cm^3, and (495 ± 45) particle/cm^3 respectively. For the September campaign, the concentration of particles were found to be (1233 ± 274) particles/cm^3 in the LBL, (651 ± 68) particles/cm^3 in the UBL, and (568 ± 70) particles/cm^3 in the FT. The particle size distribution measurements indicate that during the late dry season there was no change in the particle size distribution below (LBL) and above the boundary layer (UBL). This indicates that there was possibly some penetration of biomass burning particles into the upper boundary layer. In the free troposphere the particle concentration and size measured during both campaigns were approximately the same.

Keywords: Biomass burning, particle number concentration, Northern Territory Australia, airborne measurements.

1. Introduction

Biomass burning, including forest fires, agricultural waste burning, prescribed wild land burning, logging and land clearing slash, and burning for cooking and heating, has been identified as a major contributor of particles in the atmosphere (Areskoug, Camner et al. 2000; Dennis, Fraser et al. 2002; Uherek 2004). Previous studies have shown that most of the particles from biomass burning were found to be of a size less than 1 μm in diameter (Ferge, Maguhn et al. 2005; Reid, Koppmann et al. 2005; Wieser and Gaegauf 2005) and that their presence in the air significantly affects atmospheric processes (Shaw 1987). The effects range from acidification of clouds, rain, and fog (Nichol 1997); altering cloud microphysical processes in a small scale and mesoscale; and altering the radiation balance of the earth, both directly, by absorbing and scattering incoming solar radiation, and indirectly, by acting as cloud condensation nuclei (CCN) (Kaufman, Hobbs et al. 1998; Martins, Artaxo et al. 1998; Wurzler and Simmel 2005).

Numerous studies investigated characteristics of particle from biomass burning in several regions, such as Africa (Anderson et al, 1996; Dubovik et al, 2002, Haywood et al,2003a, Eck et al, 2003), North America (Hobbs el al, 1996, Radke et al, 1991, Dubovik et al, 2002), Eck el al, 2003), South America (Anderson et al,1996, Andreae et al, 1988, Dubovik et al,2002, Echalar et al, 1998, Eck et al, 2003, Reid et al, 1998b), and meditarian (Formenti et al, 2002). The reports showed that biomass burning particles found in different region vary in concentrations, emission factors, and sizes. The variety of particle characteristics may be due to several factors such as: intensity of fires, fuel types, moisture, weather condition, and other variables.

Very few airborne measurements of atmospheric aerosols have been conducted over the continent of Australia, with one study conducted only in the Eastern part of the continent (Gras 1991) and a few other campaigns focused on characterizing the biomass burning plumes in both the Northern Territory and parts of Indonesia (Borneo) (Gras 1999; Tsutsumi 1999). Considering the size of Australia and the scale of biomass burning that

occurs annually, both as controlled and uncontrolled burning, there is a need to gain a better quantitative insight into the biomass burning emissions in this region. Such information is essential in developing better understanding of the potential impacts of the emissions as well as input into climate change forecasting models (Rotstayn, Cai et al. 2007). To address this need a large program was undertaken involving Queensland University of Technology (QUT), the Defense Science and Technology Organization (DSTO), and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), with the main focus on characterizing biomass burning aerosols in the Northern Territory, Australia, during the 2003 dry season. The specific objective of the part of work reported here was to conduct measurements of particle size and number concentration at different heights to provide an insight into the impact of biomass burning on the vertical particle profiles. Other characteristics of aerosol such as chemical and optical characteristics (Carr, Gras et al. 2005) and size distribution (Wardoyo, Morawska et al. 2007) were reported elsewhere.

2. Experimental Methods

2.1. Study Area

The study was conducted over the large areas of tropical savannas of the Northern Territory, Australia. The dominant vegetation type of these savannas is a mixture of annual grasses, such as *Sorghum* species and perennial grasses, and tropical savanna woodland, made up of sporadic trees, predominantly the *Eucalyptus miniatia* (Wilson, Brocklehurst et al. 1990; Williams, Cook et al. 1999). A large fraction of the vegetation is burnt annually by naturally occurring fires (Russell-Smith, Ryan et al. 1997).

The climate in the savanna region of the Northern Territory is highly seasonal and has a distinctive dry and wet season. The wet season is hot and humid, occurring from November to April. The entire average annual precipitation, of over 1000 mm, nearly always occurs during this period. The rainfall pattern for the region varies greatly from year to year due to the Southern oscillation (McKeon, Day et al. 1990). In comparison, the dry season is mild to warm and extends from May to October. Naturally biomass

burning occurs during almost every dry season (Gill, Ryan et al. 2000). These fires are usually of a mild intensity in the early dry season (EDS) and of a high intensity in late dry season (LDS) (Williams, Gill et al. 1998).

2.2. Measurement Times and Locations

The airborne measurements of particle number concentration and particle size distribution were conducted during two campaigns, in June and September 2003, which were in the EDS and the LDS, respectively. The measurements were performed both in the morning and in the afternoons with the duration of each flight leg from 20 to 30 minutes. The total time spent for each measurement for every flight was approximately four hours. This included transit from Darwin to on station, a vertical stack of horizontal flight legs and return transit to Darwin. In June the flights were on the Monday, Tuesday and Thursday afternoons with the final flight on the Friday morning. In September campaign, the fights were conducted two times in the morning (Tuesday and Thursday) and two in the afternoon (Monday and Friday).

The airborne measurements were carried out along a predetermined horizontal path, that extended from a point South West (SW) of Jabiru (13.08 South (S) 132.32 East (E)) to a point North East of Jabiru (12.11 S 133.15 E), in Kakadu National Park, Northern Territory. The orientation of the flight path was chosen so that the flight track was perpendicular to prevailing wind directions on the ground. The wind was predominantly coming from the South East (SE) during the June campaign and from the North West (NW) during the September campaign. The wind direction did vary somewhat from day to day and from morning to afternoon, however the variation was in general not significant enough to influence the choice of the predetermined flight direction. Figure 1 presents a map of Australia with the enlarged top end of the Northern Territory, where the measurements were conducted. The dot spots are accumulative fires detected between 22-28 June and 21-27 September 2003. The satellite data shows that there were 39, 28, 72 and 41 hotspots detected on the 23rd, 24th, 26th and 27th of June 2003 and 3, 11, 11, and 6 hotspots on the 22nd, 23rd, 25th and 26th of September 2003, respectively. Although there were fewer fires in September 2003, the intensity of the fires in September was higher

than those occurring in June 2003. Further the majority of the fires were located in the proximity to the flight tracks.

Figure 1. Place here

The weather conditions were mainly fine, with intermittent cloud cover for the majority of days. In the mornings, the cloud cover was generally more sporadic and found at a lower heights, approximately 700-1300 m from the ground. The cloud band generally increased in intensity during the early afternoon and was at heights of 3300-4900 m off the ground. Due to an increase in number and intensity of fires later in the day, the preference was for afternoon flights, however this was not always possible due to the increased cloud cover. The altitudes for each flight were chosen in order to obtain boundary layer data alone, or a combination of boundary layer and free troposphere data. However, cloud cover at times resulted in modification of the flight plans, which is the reason for variation in the altitudes of the individual flight legs between different flights. The minimum altitude was set at 500 m, primarily for aircraft safety reasons, and the maximum altitude flown was 6500 m. A summary of the flight details is given in Table 1 including time, location and the purpose of each flight. Times are given in Australian Central Standard Time (CST), which is 9.5 hours ahead of coordinated universal time (UTC).

Table 1. Place here

2.3. Instrumentation Set Up

A range of scientific instrumentation was fitted to an aircraft (Beech Super King Air B200T) that has been configured for scientific research. This equipment was either purpose built for aircraft sampling or was modified to be applicable for this purpose. An isokinetic inlet was fitted externally to the fuselage of the aircraft, which was fed into the cabin of the aircraft to provide suitable sampling lines for a range of aerosol measuring instruments. The particle measurements were conducted using a TSI Scanning Mobility Particle Sizer (SMPS) consisting of a TSI 3010 Condensation Particle Counter (CPC) and

a TSI 3080 Electrostatic Classifier (EC). The SMPS was mounted in a single, two levels, 19 inch rack, with anti-vibration mounts, and was located on the left hand side of the aircraft.

The SMPS was operated with a sheath air flow of 3 L/m and a sample flow of 0.3 L/m. The scanning time and retrace time were set 120 and 30 seconds, respectively. The multiple charge correction algorithm was also employed. The SMPS was calibrated daily using 100 nm size PSL before each flight. The measurement range of the SMPS was set up depending on the atmospheric pressure at which the measurements were conducted, such that when the pressure was lower the bottom cut point became higher. The bottom cut points were calculated at the beginning of each path and the values were entered manually into the software.

3. Results and Discussion

The particle concentrations measured as a function of height during the June campaign are presented in Figure 2. Each point on the graph represents the average particle concentration, as well as the standard deviation, calculated at each height.

Figure 2. Place here

In general, the particle concentrations measured on each day during the June campaign showed similar trends, with the particle concentrations being relatively high below 1800m and decreasing as the height increased above 1800m. At the height below 1800m, the average concentration was around 900 particles/cm^3 for the 23rd and 24th of June, and 580 and 500 particles/cm^3 for the 26th and 27th of June, respectively. On most days the decrease in concentrations to approximately 350 particles/cm^3, occurred at a height of around 2000m. The drop in particle concentration appears above the boundary layer height, that varied between 1700 and 2000m. The average concentrations of particles measured above 3900m (in the free troposphere) in June were around 400 particles/cm^3. The only exception was on the 24th of June, when the concentration in the FT was larger

and decreased to approximately 550 particles/cm^3 and remained fairly constant even up to height of 6500m. It can be seen that the standard deviation of the concentrations is high below 1800m, which implies that the variation in the concentrations of particles up to this height is relatively large over the flight paths. This is likely to be a result of the fire locations close to the flight paths with not enough mixing.

The boundary layer height was about 1700m, 2000m, 1800m and 1700m for the 23rd, 24th, 26th and 27th of June, respectively. The boundary layers calculated for the September campaign were approximately 2000m, 1800m, 2000m and 2000m for the 22nd, 23rd, 25th and 26th of September, respectively.

The highest observed standard deviation was for the measurements on the 24th of June 2003, when the average and standard deviation of particle concentrations measured below 1800 m was found to be (900 ± 1000) particles/cm^3. The high standard deviation shows that there was a large variation in the measured concentrations along the flight path, which in this case can be attributed to the flight path passing directly through the smoke plume. An illustration of the variation of the particle number concentration over the flight paths for 2 heights are presented on Figure 3 together with the location of individual fires and wind direction. The location of the individual fires (hotspot data) was provided by CSIRO through the Sentinel service (http://www.sentinel.csiro.au). There were more than 30 fires detected on that day with most hotspots located close to the flight paths. The largest concentration of particles measured at 800 m was 4093 particles/cm^3, obtained when the aircraft was at 12.1 S 133.3 E. A relatively high concentration of particles was also found at 1800 m, where the concentration of particles measured 990 particles/cm^3 at 13.0 S 132.7 E. Considering the close location of fires and the NW direction of wind the high concentration measured were due to the flight path directly crossing the plume. This has been confirmed through direct visual observations during the flight.

Figure 3. Place here

The measurements carried out on the 26th and 27th of June found similar concentrations for all the measured heights, with the concentrations below the boundary layer being

lower than those measured on the previous days. This is most likely due to the fact that the location of the fires and the wind direction on these two days caused the smoke to be blown away from the flight paths.

Figure 4. Place here.

In general, the concentrations of particles measured during the September campaign were higher than those measured during the June campaign, despite the smaller number of fires during the September campaign. Figure 4 shows the concentration of particles measured for different heights during the September campaign.

Similar trends as in the June campaign were also observed with the vertical distribution of the particle concentrations significantly dropping above the boundary layer. A particle concentration of around 500 particles/cm^3, similar to the June flights, was observed for larger heights in the FT. Another interesting thing to note is that during 3 out of 4 September flights, there was an increase in the particle concentration just below the inversion layer.

In order to compare the particle concentrations for the two campaigns, across all of the altitudes measured, particle concentration was averaged over each height within each campaign. This is presented in Figure 5a, whilst Figure 5b shows the average count median diater (CMD) as a function of height for each campaign. The altitudes were divided into 3 regions: Region I - lower boundary layer (LBL), for heights below 1800 m for the June campaign and below 1950 m for the September campaign; Region II - upper boundary layer (UBL), for heights between 2000-3900 m; and Region III - free troposphere (FT), for heights above 3900 m.

Figure 5. Place here

The average and standard deviation of the particle concentration in Region I presented in Figure 5a was (685 ± 245) particles/cm^3 for the June campaign and (1233 ± 274)

particles/cm^3 for the September campaign. The concentration decreased in Region II to (365 ± 183) particles/cm^3 and (651 ± 68) particles/cm^3 for June and September campaigns, respectively. The concentration of particles in Region III was (495 ± 45) particle/cm^3 for June campaign and (568 ± 70) particles/cm^3 for September campaign.

In both campaigns, the average particle concentration above the boundary layer (moving from Region I to Region II) decreased by approximately 47%. Although there are no similar results for this region airborne measurements of particle emissions from biomass burning in Amazonia observed that the decrease in particle concentrations from the boundary layer to the cloud detrainment layer and free troposphere was approximately 20% (Guyon, Frank et al. 2005). One of the reasons for a larger observed entrainment in our measurements could be due to stronger inversion layers. On the other side the particle concentrations in Region III were more or less the same in both campaigns as these particles are due to long range transport within the free troposphere.

4. Conclusions

The average concentration of particles during the September campaign was larger than in June, for all altitudes in the first two regions. The difference between the two campaigns was statistically significant for all heights except between 850-1000 m (which is due to the very high standard deviations in June when the aircraft passed through several plumes whilst at these heights). The June flights show a decrease in particle concentration with an increase in altitude whilst the September measurements show an increase up to the boundary layer. This indicates that the plumes in September had been trapped for a longer time just below the inversion layer and therefore have had a longer time to age.

This is further confirmed by Figure 5b which presents the average count median diameter (CMD) as a function of altitude for both campaigns. The data clearly shows that the particles in regions I and II were much larger in September with a CMD of around 130 nm compared to a CMD of only 90 nm in June. If one observes the hotspot data it shows that the fires were located close to the flight paths for the June campaign and hundreds of

kilometers from the flight paths during the September campaign. This means that most of the particles measured during June campaign were coming from fresh plumes emitted by biomass burning located close to the flight paths and could be considered as 'fresh smoke particles'. Conversely, the larger 'aged smoke particles' observed in September were mostly from aged plumes, where the particles had been trapped in the atmosphere for a period of time and were allowed to age and coagulate and increase in size. Measurements of the particle size distributions emitted directly from burning grasses in laboratory conditions show that the particle size is closer to the ones observed during the June campaign (Wardoyo, Morawska et al. 2007). This indicates that the particles measured during the June campaign are more likely to come from a closer source than the ones observed in the September campaign.

In the early dry season, the June campaign, it can be seen that CMD dropped quite sharply from an average of 85 nm in Region I to 60 nm in Region II (UBL) and remained constant throughout the second region. This indicates that the particles produced by biomass burning during the early dry season did not penetrate through the inversion layer and therefore the particles in Regions II and III most likely have come from other sources and could possibly be a result of long range transport. In contrast the CMD measured in Region II (UBL) during the late dry season, the September campaign, did not show a significant change with the particles remaining reasonably large, above 100 nm. This indicates that there was possibly some penetration of biomass burning particles into the upper boundary layer. In the free troposphere, Region III, the particle concentration and size measured during both campaigns were approximately the same. This indicates that these particles come from another source and could be a result of long range transport or particle production due to the condensation of sulphuric acid (Clarke and Kapustin 2002).

Back trajectories from both campaigns indicate that the origin of the air masses were from the marine sectors. Taking into account that the average concentrations of particles in the marine boundary area are bellow 500 cm^{-3} the observed increase in particle concentration due to biomass burning is significant.

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Figure Captions

Figure 1. Location of the flight tracks. The two maps zoomed in over the flight path (indicated by the black line) at the Northern end of the Northern Territory, show satellite fire spot data for 22-28 June 2003 (left) and 21-27 September 2003 (right) (source: http://www.sentinel.csiro.com.au).

Figure 2. The measured concentrations of particles as a function of flight height for the June campaign.

Figure 3. The particle concentrations along the flight paths, measured on 24th June 2003 at 800 m and 1800 m. The large triangles show the location of fires. The arrows show wind directions at the noted heights.

Figure 4. The measured concentrations of particles as a function of flight height for the September campaign

Figure 5. (a) Average particle concentrations and (b) Count Median Diameter (CMD) measured during June and September campaigns.

Tables

Table 1. Summary of measurement flight plans

Campaign	Flight #	Date/Start time	Flight Leg Altitude (km)	Flight leg duration (mins)
June 2003	1	23rd 14:00	0.2, 1(x2), 1.5, 2, & 2.6	30
	2	24th 13:30	0.8, 1.8, 3.3, 4.9, & 6.5	30
	3	26th 13:30	0.5, 0.8, 1.1, 1.5, 2.1, & 2.4	20
	4	27th 07:30	0.5, 0.8, 1.5, 2.1, 3.3, & 4.9	20
September 2003	1	22nd 13:15	0.7, 1.3, 1.6, 2, 4.9, & 6.5	20
	2	23rd 08:00	0.5, 0.8, 1.3, 1.6, 2, 2.6, & 3.3	20
	3	25th 07:00	0.5, 0.8, 2, 2.6, 3.3, 4.9, & 6.5	20
	4	26th 11:30	0.5, 1, 1.3, 2, 2.6, & 3.3	20

Figures

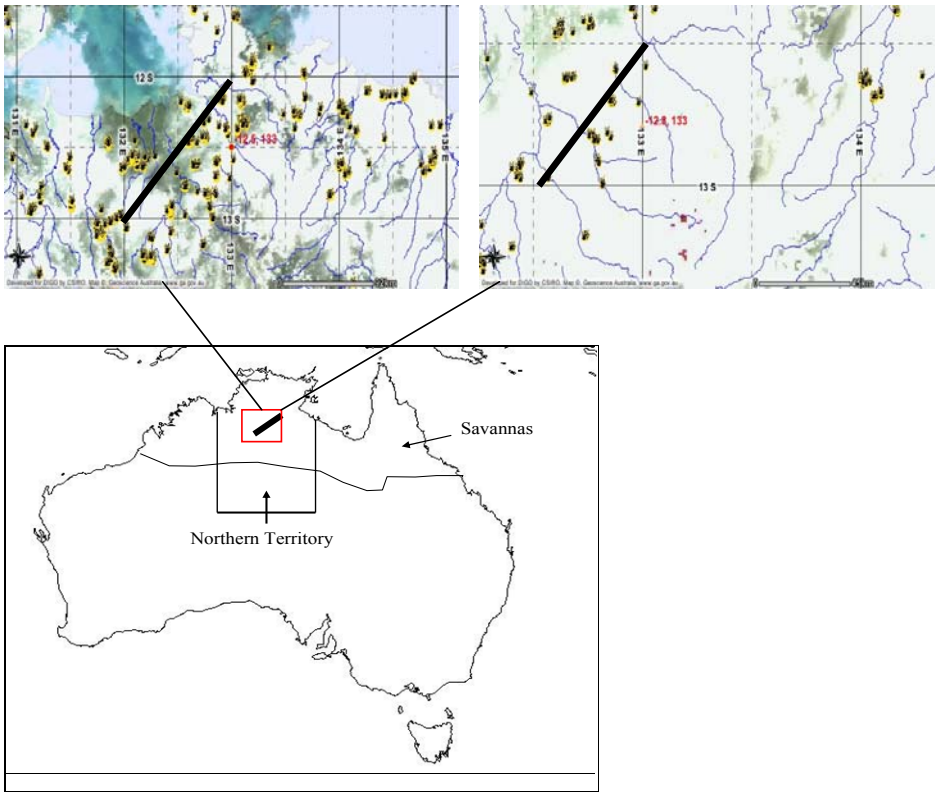

Figure 1

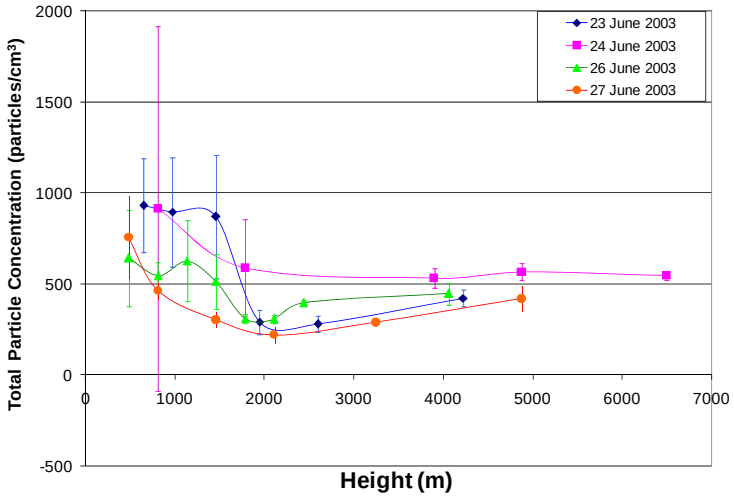
23 June 2003
24 June 2003
26 June 2003
27 June 2003
Total Particle Concentration (particles/cm³)
2000
1500
1000
500
0
-500
0
1000
2000
3000
4000
5000
6000
7000
Height (m)

Figure 2

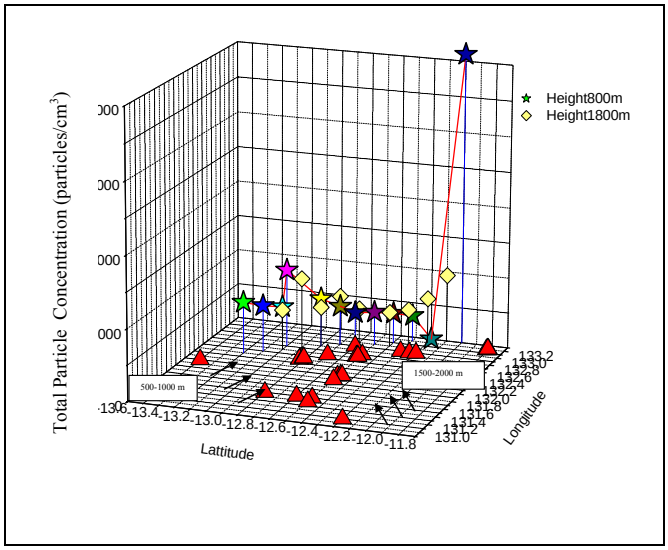
Total Particle Concentration (particles/cm3)
Height800m
Height1800m
500-1000 m
1500-2000 m
Lattitude
Longitude

Figure 3

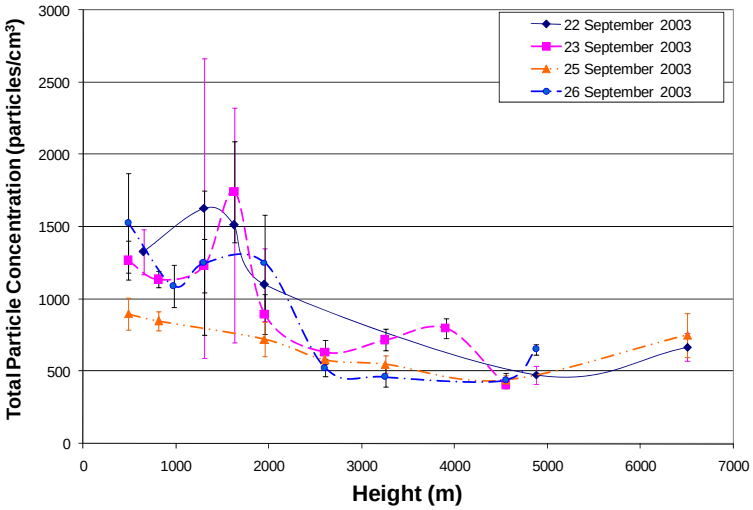
Total Particle Concentration (particles/cm³)
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
Height (m)
22 September 2003
23 September 2003
25 September 2003
26 September 2003

Figure 4

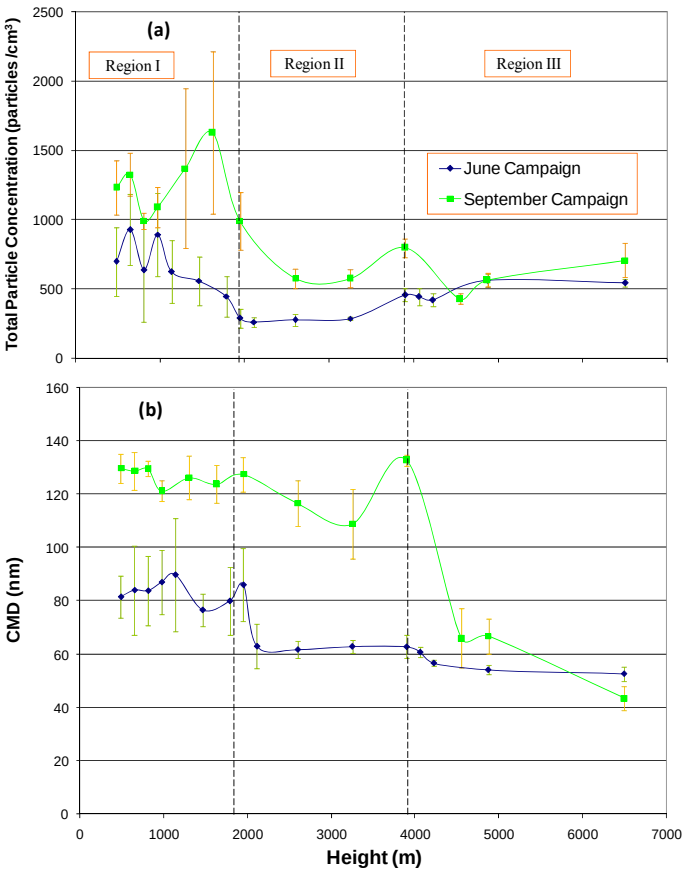
(a)
Region I
Region II
Region III
June Campaign
September Campaign
Total Particle Concentration (particles /cm³)
2500
2000
1500
1000
500
0
(b)
CMD (nm)
160
140
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Height (m)

Figure 5